REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	2 July 1993	Final

4. TITLE AND SUBTITLE

"Unsteady Flow Distortion Past Blades; Source of Noise Generation in Rotating Flows"

5. FUNDING NUMBERS

N00014-89-J-1799

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8. PERFORMING ORGANIZATION REPORT NUMBER

533633 Final

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

ARI-CLOSEOUT REPORT
(June 25, 1993)
"Unsteady Rotating Flows as Hydroacoustic Sources"

1. **GRANT TITLE:** UNSTEADY FLOW DISTORTION PAST BLADES: SOURCE OF NOISE GENERATION IN ROTATING FLOWS

   PRINCIPAL INVESTIGATOR AND INSTITUTION: PROFESSOR DONALD ROCKWELL, LEHIGH UNIVERSITY

2. **TOTAL FUNDING AND TERM OF RESEARCH:** $350,000 FOR A PERIOD JUNE, 1989, THROUGH OCTOBER, 1992 *(six month no-cost extension)*

3. **RESEARCH OBJECTIVES**

   The overall goals of this program are to:

   - Determine the instantaneous flow structure past blading and interpret it in terms of pressure sources using high-image-density particle image velocimetry. In turn, these pressure source terms are to be decomposed into vorticity-related and rate-of-strain related contributions.

   - Establish active (open loop) control concepts for flow past blading. Generic leading- and trailing-edge interactions will be addressed. Control concepts are to incorporate harmonic, amplitude- and frequency-modulated disturbances. Attempts will be made to:

     - Destabilize normally coherent fluctuations into multiple-spectral or broadband distributions;

     - Restabilize modulated fluctuations to a periodic state; and

     - Modify the level of broadband fluctuations.

   - Implement active control concepts in a unique, actively-controlled radial flow machine, allowing arbitrary inflow and impeller perturbations. The flow structure in the machine is to be subjected to various phase-shifting concepts in order to optimize the flow control.

   - Develop new approaches to high-density particle image velocimetry, involving innovative approaches to acquisition of images, as well as processing and post-processing of images to provide global, instantaneous insight.

5. PAPERS

5a PAPERS SUBMITTED TO REFEREED JOURNALS

Nakano, M. and Rockwell, D.1993 "Flow Structure in the Frequency-Modulated Wake of a Cylinder", accepted for publication in *Journal of Fluid Mechanics.*

Takmaz, L. and Rockwell, D. 1993 "Unsteady Flow Structure and Surface Pressure Due to Translation of a Cylinldrer Past an Elliptical Leading-Edge", submitted to *Journal of Fluids and Structures.*

Akin, O. and Rockwell, D. 1993 "Actively-Controlled Radial Flow Pumping System: Manipulation of Spectral Content of Wakes and Wake-Blade Interactions", submitted to *Journal of Fluids Engineering.*

Akin, O. and Rockwell, D. 1993 "Flow Structure in a Radial Flow Pumping Sytem Using High-Image-Density Particle Image Velocimetry", submitted to *Journal of Fluids Engineering.*

Akin, O. and Rockwell, D. 1993 "Interaction of Zones of Flow Separation in a Centrifugal Impeller-Stationary Vane System" submitted to *Experiments in Fluids.*

Akin, O. and Rockwell, D. 1993 "Flow Structure from the Trailing-Edge of a Stalled Impeller Blade", submitted to *Journal of Fluids and Structures.*

Lin, J.-C. and Rockwell, D. 1993 "Cinematographic System for High-Image-Density Particle Image velocimetry. Submitted to *Experiments in Fluids.*

Towfighi, J. and Rockwell, D. 1993 "Flow Structure from an Oscillating Non-Uniform Cylinder: Generation of Patterned Vorticity Concentrations", submitted to *Physics of Fluids.*

5b PAPERS PUBLISHED IN REFEREED JOURNALS

Lotfy, A. and Rockwell, D. 1993 "The Near-Wake of an Oscillating Trailing-Edge: Mechanisms of Periodic and Aperiodic Response", *Journal of Fluid Mechanics* (in press).

Konak, S. and Rockwell, D. 1993 "Control of the Spanwise Strucure of a Bluff-Body by Chagnes in Boundary Layer Thickness at Separation", *Physics of Fluids A*, Vol. 2, pp. 509-511.

Magness, C., Towfighi, J., Akin, O., Corcoran, T. and Rockwell, D. 1993 "High-Image-Density Particle Image Velocimetry Using Laser Scanning Techniques", *Experiments in Fluids*, Vol. 14, pp. 181-192.

Nakano, M. and Rockwell, D. 1993 "The Wake from a Cylinder Subjected to Amplitude-Modulated Excitation", *Journal of Fluid Mechanics*, Vol. 247, pp. 79-110.

Robinson, O. and Rockwell, D. 1993 "Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", *Experiments in Fluids*, Vol. 14, pp. 257-270.

Nuzzi, F., Magness, C. and Rockwell, D. 1992 "Three-Dimensional Vortex Formation from an Oscillating, Nonuniform cylinder", *Journal of Fluid Mechanics*, Vol. 238, pp. 31-54.

Nakano, M. and Rockwell, D. 1991 "Decoupling of Locked-In Vortex Formation by Amplitude-Modulated Excitation", *Journal of Fluids and Structures*, Vol. 5, pp. 455-458.

Nakano, M. and Rockwell, D. 1991 "Destabilization of the Karman Vortex Street by Frequency-Modulated Excitation", *Physics of Fluids*, Vol. 3, pp. 723-725.

Nuzzi, F., Magness, C. and Rockwell, D. 1991 "Period-Doubling in the Wake of a Trhee-Dimensional Cylidner", *Physics of Fluid,* Vol. 3, pp. 1477-1478.

Gursul, I. and Rockwell, D. 1991 "Effect of Concentration of Vortices on Streakline Patterns", *Experiments in Fluids*, Vol. 10, pp. 294-296.

Gursul, I., Lusseyran, D. and Rockwell, D. 1990 "On Interpretation of Flow Visualization of Unsteady Shear Flows", *Experiments in Fluids*, Vol. 10, pp. 294-296.

Gursul, I. and Rockwell, D. 1990 "Vortex Street Impinging Upon an Elliptical Leading-Edge", *Journal of Fluid Mechanics*, Vol. 211, pp. 211-242.

5c PAPERS PUBLISHED IN NON-REFERRED JOURNALS

Invited Lecture: "Quantitative Visualization of Bluff-Body Wakes Via Particle Image Velocimetry", International Union of Theoretical and Applied Mechanics Symposium on Bluff-Body Wakes", Goettingen, Germany, 1992 (to be published by Springer-Verlag; eds. H. Eckelmann and J. M. Graham).

Invited Presentation: "Quantitative Interpretation of Complex, Unsteady Flows via High-Image-Density Particle Image Velocimetry", SPIE (Society of Photo-Optical Engineers) International Symposium on Optics, Imaging and Instrumentation, San Diego, California, 11-16 July (to be published as SPIE Proceedings, Volume 2005) (with J.-C. Lin).

Invited Lecture: "Active Control of Globally-Unstable Separated Flows", International Symposium on Nonsteady Fluid Dynamics, ASME FED-Vol. 92 (edited by J. A. Miller and D. P. Telionis), pp. 379-394.

6. TECHNICAL REPORTS

Three annual reports entitled "Unsteady Flow Distortion Past Blades: Source of Noise Generation in Rotating Flows", submitted to ONR October, 1989; October, 1991; and May, 1993.

7. BOOKS PUBLISHED

An Engineering Guide to Flow-Induced Vibrations, Balkema Press, Rotterdam (in press) (with E. Naudascher)

8. NUMBER OF BOOK CHAPTERS PUBLISHED:

None

9. PATENT APPLICATIONS

None

10. SIGNIFICANT PRESENTATIONS

10a TOTAL NUMBER

Fourteen

10b LIST OF TOP THREE

Invited Lecture: "Quantitative Visualization of Wakes Via Particle Image Velocimetry", International Union of Theoretical and Applied Mechanics Symposium on Bluff-Body Wakes, Goettingen, Germany, 1992 (to be published by Springer-Verlag; eds. H. Eckelmann and J. M. Graham).

Invited Lecture: "Active Control of Globally-Unstable Separated Flows", International Symposium on Nonsteady Fluid Dynamics, ASME FED - Vol. 92 (1990) (edited by J. A. Miller and D. P. Telionis), pp. 379-394.

Invited Presentation: "Quantitative Interpretation of Complex, Unsteady Flows via High-Image-Density Particle Image Velocimetry", SPIE (Society of Photo-Optical Engineers) International Symposium on Optics, Imaging and Instrumentation, San Diego, California, 11-16 July 1993 (to be published as SPIE Proceedings, Volume 2005) (with J.-C. Lin).

(Unable to accept a number of invited lectures and seminars at various universities and technical meetings due to research commitments.)

11. AWARDS

Paul B. Reinhold Professorship of Mechanical Engineering and Mechanics (1988 - present)

Joseph and Eleanor Libsch Research Award (1989) (presented to Lehigh faculty member with most outstanding research accomplishments).

12. POST-DOCS SUPPORTED

Number supported*: Two

Total man-months*: Eighteen

* Visiting Scientist status

13. GRADUATE STUDENT SUPPORT

Number supported: One

Total man-months: Eleven

Additional students, whose stipends were paid by Teaching Assistantships, had their research costs supported by this program.

14. MOST SIGNIFICANT PUBLICATIONS (abstracts only)

"Actively-Controlled Radial Flow Pumping System: Manipulation of Spectral Content of Wakes and the Wake-Blade Interactions" by O. Akin and D. Rockwell (submitted to *Journal of Fluids Engineering*)

A unique pumping system allows independent control of inflow and impeller perturbations, as well as the phase shift between them. The basic configurations of an impeller and an impeller-diffuser blade system have been investigated, with the objective of manipulating the spectral content of the unsteadiness through the system. Substantial alteration of discrete spectral components can be obtained. A central feature is the generation of a number of nonlinear interaction components, corresponding to sum and difference frequencies, of the forcing- and blade-passing frequencies in their harmonics. The

proper choice of perturbations conditions is possible to attenuate flow perturbation as well as to alter the magnitude to the blade passing component and its harmonics.

"Interaction of Zones of Flow Separation in a Centrifugal Impeller-Stationary Vane System", by O. Akin and D. Rockwell (submitted to *Experiments in Fluids*).

In a radial flow pump operating in off-design conditions, regions of stall can exist on the rotating impeller blade and on the downstream diffuser blade, vane or tongue. The instantaneous flow structure of these stall regions is characterized using high-image-density particle image velocimetry. This characterization shows that interaction of stall zones can generate complex patterns of vorticity concentrations. In turn, these vorticity concentrations are related to sources of unsteady stagnation enthalpy. The form of these patterns is strongly dependent on the instantaneous location of the impeller trailing-edge relative to the leading-edge of the vane.

Comparison of instantaneous with ensemble-averaged images shows that the flow structure in the gap region between the impeller and the vane are highly repetitive. Away from this region, in particular in the separated shear layer from the vane, the non-repetitive nature of the vorticity field is manifested in substantial reduction of peak levels of vorticity and the ensemble-averaged image relative to the instantaneous image.

The three-dimensional flow structure resulting from the separation zone interactions was characterized via end views of the flow patterns. Particularly pronounced concentrations of vorticity can occur in this plane. They tend to be located in the shear layer of the outer edge of the large-scale separation zone. These vorticity concentrations are, however, highly nonstationary for successive passages of the impeller blade. Ensemble-averaging reveals that they persist primarily on the end walls of the diffuser.

"Flow Structure in the Frequency-Modulated Wake of a Cylinder" (by M. Nakano and D. Rockwell), *Journal of Fluid Mechanics* (in press).

A cylinder is subjected to frequency-modulated (FM) excitation and the structure of its wake is characterized in terms of the modulation frequency and frequency deviation. It is possible to destabilize or restabilize the degree of organization of the vortical structures in the near-wake and thereby substantially manipulate the spectral content, relative to the case of purely sinusoidal excitation. These processes of destabilization and restabilization are attained by varying the frequency deviation while holding the modulation frequency constant or vice-versa. A phase-locked periodicity of the near-wake response is attainable at the period of the modulation frequency, as well as its subharmonics. This periodicity, or lack of it, is related to the degree of organization of the wake.

The structure of the far-wake is strongly dependent upon the nature of the near-wake modification. Either coherent or destabilized wake structure can be induced in the far-wake at a given value of nominal excitation frequency by employing appropriate FM excitation.

15. ACCOMPLISHMENTS

- The first instantaneous, wholefield vorticity and pressure source distributions in a rotating system have been obtained.

- The major pressure source terms have been related to identifiable regions of vorticity. Multiple concentrations of vorticity have been interpreted in terms of arrays of deterministic pressure source terms.
- Major classes of complex flow structure occurring past generic types of blading and within actual rotating machinery have been defined on a quantitative basis in terms of flow separation and development of stall.

- New control concepts have been developed for manipulating vorticity fields and pressure source terms. They involve:

    - Implementation of various types of phase shift, e.g., shift between the inflow perturbation and arrival of the impeller blade, in order to alter the timing of the vorticity field-blade interaction and thereby the nature of the pressure source terms.

    - Perturbation of the blade (body) relative to the flow or vice-versa, with amplitude- or frequency-modulated disturbances. Dramatic alterations of the vorticity field and the corresponding spectral content can be attained. Transformations between a large number of spectral components and a single, focused component are attainable. Moreover, it is also possible to generate a shift in the broadband (background) level.

- Innovative types of high-image-density particle image velocimetry have been developed. High speed laser scanning (in contrast to classical, double-pulsed illumination) allows both spatial and temporal resolution of instantaneous PIV characterization of the flow. New types of parallel processing techniques for evaluation of instantaneous images have been developed. Highly time-resolved image acquisition, involving cinematography with image shifting, allows volume representations of iso-vorticity.

- New types of post-processing techniques, focusing on instantaneous wholefield information have been developed. Variable spatial filtering, instantaneous spatial vorticity correlations, and ensemble-averaging techniques allow new insight into the vorticity distribution and instantaneous pressure source terms.

16. SIGNIFICANT TRANSITIONS

- Wholefield instantaneous characterizations of complex flows have allowed establishment of a framework based on vorticity and stagnation enthalpy concepts for identifying pressure source terms. This framework has been communicated to appropriate Naval laboratories, as well as to commercial pump manufacturing concerns, including Ingersoll-Dresser, Gould, Crane and to related groups at, for example, General Electric and Westinghouse.

- New techniques of laser-diagnostics of complex flows in pump systems have been conveyed, in a practical sense, to most of the foregoing pump manufacturers. These diagnostic approaches provide new capabilities in the research, development, and operational stages.
- New concepts of active control, involving perturbations of inflow, as well as of the pump impeller, have been communicated to the foregoing Naval laboratories and pump manufacturers. These concepts allow altering the spectral content of the noise generation not only by application of control, but also by analyzing self-generated perturbations through pumping systems.

17. IMPACT OF RESEARCH

Interpretation of the flow pattern, more specifically the vorticity distribution, in a global, instantaneous sense, allows proper determination of the instantaneous pressure source terms and a framework for controlling them. This approach moves away from traditional attempts to measure pressure fluctuations via transducers at specified locations on blading of rotating machinery. To be sure, future research and development will no doubt include both of these approaches in a complementary fashion. Rapid development of laser illumination and image acquisition techniques, however, will make global characterizations of complex flow patterns even more appealing to development and field engineers and provide a rational basis for in-situ diagnostics.

Identification of major pressure source terms in this investigation suggests alterations of geometry and operating conditions of rotating flow systems, in order to minimize pressure source terms. For example, proper modification of the geometry and flow patterns of the gap region involving encounter of a rotating flow with a stationary blade, as well as attenuation of regions of trailing-edge separation and leading-edge stall over blading, can lead to modification of source terms.

In a research sense, the basis now exists for interactive development of large-scale computations of hydro- and aeroacoustic noise sources and implementation of experiments providing wholefield, instantaneous images.